CHARGING SYSTEMS FOR ELECTROSTATIC GENERATORS

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ELECTROSTATIC GENERATORS

by

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SUMMARY OF SYMBOLS USED

Primary Symbols

d - distance from ion to charge increment
E - field strength
f - friction factor
g - acceleration due to gravity

h - transport distance
I - charging current
k - ion mobility
l - distance from ion to charge increment

p - gas pressure
P - power required to force gas through system
q - charge density per unit length of tube
Q - volume rate of flow

r - radius of ionized gas stream
R - radius of tube
u - velocity of ion
v - velocity of gas

V - voltage on collecting electrode
x - distance down tube
  - gas density

Subscripts

1, 2, 3 - indicate particular values
opt - optimum
r - in radial direction
x - in x direction

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ABSTRACT

This paper examines the possibilities of using ions in a flowing gaseous medium for charging electrostatic generators of the Van de Graaff type. Within the limits of the experiments made, it is concluded that this charging system could be used profitably to replace the conventional belt in certain cases. For low voltage, high current requirements where a long service-free life is desired, the charging system investigated appears particularly advantageous.

INTRODUCTION

Electrostatic generators, primarily of the Van de Graaff type, have assumed a position of some importance in nuclear physics and x-ray technology in recent years, primarily because they offer a means of generating high electric potentials that can be controlled very precisely (1, p. 1417). In the conventional type, the charge is sprayed (usually by corona discharge from needle points) onto a moving endless belt. This belt conveys the charge into the interior of a hollow electrode. There the charge is removed by a fine wire or set of needle points.

One of the limitations of the Van de Graaff generator is that it is capable of producing only small currents. Wide belts and fast speeds are necessary to produce charging currents of the order of one milliampere (2). These high speeds cause considerable mechanical difficulty.

As the result of the above, it seems fair to ask whether or not other means may exist for conveying the charge, and whether such means might possess greater charge carrying ability or greater mechanical simplicity. At least a partial answer to this question will be attempted in this paper.

REVIEW OF THE LITERATURE

The greater part of the published work in the field has been done by M. Pauthenier and his associates in France. The use of gaseous ions (3), charged droplets (4), and dust particles (5) have been the subject of either theoretical or experimental study or both.

Since the charging ions in practically all large electrostatic generators originate in a brush discharge in a gas, it would seem, on first examination at least, that the most elegant method for charging the collector would be to form the ions in a moving gas stream. The ions would then be conveyed from source to collector by the gas stream itself. This method has been studied previously by Mme. Moreau-Hanot (3). A theoretical expression is presented for the relationship between charge transported, transport distance, radius of the stream, gas mobility and gas velocity. The expression given is as follows:

$$I = \frac{r^2u^2}{4kh}$$

where:

r = radius of ionized gas stream

I = current contained within stream of radius r

k = ion mobility

h = transport distance

u = ion velocity parallel to axis of tube.

Assumptions and derivation were not given by Moreau-Hanot, but a derivation leading to a similar result is developed under the section entitled, "Analysis of the Problem".

Moreau-Hanot obtained the following experimental results, reproduced below in entirety, (3, p. 1169).

Table 1

Experimental Results of Moreau-Hanot

Run	R (cm.)	h (cm.)	u (m./s.)	I (μ a.) theo.	I (μ a.) meas.
1	2.5	12.5	34	1	1
2	2.5	7.5	34	1.7	2.2
3	2	8	65	3.6	3.4
4	2	8	90	6.8	5.6
5	2	8	122	12.4	8.8
6	2	24	95	2.6	1.6
7	2	24	122	4.1	2.2

It was concluded that the high mobility of the ions would prevent an adequate charging current from being carried the distance dictated by the insulation requirements of the high voltage electrode. Efforts to reduce the carrier mobilities, by using vapors, aerosols, and dust particles, have culminated in the design and construction of a number of generators using dust (5).

ANALYSIS OF THE PROBLEM

The preceding examination of the literature seems to indicate that the high mobility of gaseous ions renders impractical the use of an ionized gas stream as a charge carrier. The conclusions of the French investigators seem to be based, however, on the assumption that a large transport distance will be required. This condition follows from the premise that the high voltage electrode will be insulated by air at normal atmospheric pressure. The development of electrostatic generators insulated by gases such as SF_6 at high pressure (6) brings about a drastic reduction in the distance the charge must be transported. Simultaneously, the use of gas of high density as the charge carrier causes a reduction in the ion mobility. These two facts indicated that a re-examination of the possibility of using ions in a flowing gas stream might lead to more favorable results. Tests on methyl methacrylate (6) have indicated that a dielectric strength of .88 MV/inch can be developed with $1\frac{1}{4}$ inch samples. SF_6 under pressure may develop even greater dielectric strength. The minimum transport distance will then be a function of the dielectric strength of the tube used to carry the gas stream. Apparently, a transport distance

of less than two inches would be required for a one million volt generator.

All experimental evidence on the mobility of positive ions, which are of primary interest here, indicatrs that the mobility varies inversely with the density over a wide range of pressures (7, p. 126). Since our analysis indicates that the current transported a given distance should vary inversely with the mobility, it should vary directly with the density in a given gas.

The current that can be transported a fixed distance in a certain size tube, by a stream of air at atmospheric pressure, could perhaps be considerable increased by using a heavy gas at high pressure. Pressures of 20 atm. using sulfur hexafluoride, the molecular weight of which is 146, would therefore be expected to increase the current obtainable with air at one atmosphere by a factor of $20 \times \frac{146}{29} = 100$. This assumes, in the absence of experimental data, that the mobility is inversely proportional to the molecular weight. That this assumption is reasonable may be shown by comparing the mobilities of air ions with CO_2 and SO_2 as shown in Table 2.

All gases do not follow this relationship, however, so that experimental data is needed on the mobility of SF_6 ions. The above observed values will be used in subse-

Table 2

Mobilities of Positive Ions in Molecules of the Same Gas

Gas	$K_{air} M_{air}/M_{gas}$	$K_{obs.}$ (7, p. 126)
Air	1.3	1.3
CO_2	.86	.80
SO_2	.56	.56

quent calculations.

Extrapolating the data from Run (2) of Moreau-Hanot's to a shorter distance of 2 inches by means of the formula presented would give a charging current of about 3 a. If this could then be increased by a factor of 100 by increasing the gas density, we could expect to obtain a current of about 300 a. in a device using an ion stream about 2 inches in diameter, moving at a velocity of about 100 ft./sec.

That the above current can be obtained with a reasonable power expenditure may be shown readily. The power expended in overcoming the frictional pressure drop will be as follows:

$$P = Q \Delta p \quad ,$$

where Q is the volume flow rate of the gas and Δ p is the pressure drop

$$\Delta p = f \frac{h}{D} \frac{v^2}{2g} \quad ,$$

where f is a friction factor, is the gas density, h is the path length, D is the stream diameter, v is the gas velocity and g is the acceleration of gravity. With a high voltage on the collector

$$v = u + kE_x \quad .$$

If the axial electric field (E_x) is substantially uniform, we can say

$$v = u + k_o \frac{\rho_o}{\rho} \cdot \frac{V}{h} \quad ,$$

where V is the potential of the collector, k_o is a reference mobility, $_o$ is a reference density, and ρ is the operating density. We will assume a total circuit length equivalent to fifteen times the transport distance. Using a voltage of 1 MV, a distance of 2 inches, an ion velocity of 100 ft./sec., and a density ration of 100 compared to air at standard conditions, and using the corresponding ion mobility, we get

$$v = 100 + \frac{1.4 \times 10^{-3}}{100} \cdot \frac{10^6 \times 12}{2}$$

$$= 184 \text{ ft./sec.,}$$

but

$$Q = \frac{D^2 v}{4}$$

$$= \frac{\times 2^2 \times 184}{144 \times 4} = 4 \text{ ft.}^3\text{/sec.}$$

Taking f = .01 for smooth pipe,

$$p = .01 \times .07 \times 100 \times \frac{2}{2} \times \frac{184^2}{64.4} \times 15$$

$$= 555 \text{ lbs./ft.}^2$$

Then

$$P = 2220 \text{ ft. lbs./sec.} = 4.04 \text{ horsepower.}$$

This is the power expended in forcing the gas through the charging circuit. If we assume that the blower efficiency will be 50%, the driving motor must be of 8.1 horsepower. This compares with the 10 horsepower motor used to drive the belt in the generator of reference (1) and the 2 horsepower used in the generator of reference (6).

It should be noted that the particular combination of gas velocity and tube diameter was chosen to fit existing experimental data, and does not necessarily represent the optimum choice for minimum power.

We can conclude that if the expression

$$I = \frac{r^2u^2}{4kh} \quad ,$$

which has formed the basis for the above calculations, holds over a wide range of the variables, the transport of gaseous ions by a flowing stream may be a useful method for charging electrostatic generators.

Since the formula was presented without derivation, we have no a priori knowledge of any assumptions made that might limit the validity of the relation. We will therefore attempt a derivation here.

We will make the following initial assumptions: The gas moves down the tube with a constant velocity which is

non-turbulent and uniform over the cross section. There is no field present except that due to the ions themselves. All ions originate at a needle point located at point "0" (Figure 1). These ions will remain within a surface of revolution "S" which is defined by the trajectory of the outermost ion.

The ions downstream from any station "x_1" will tend to increase or decrease the field component "E_{r1}", depending on whether they are located at a radius lesser or greater than r_1. We will assume the ion distribution to be such that the net contribution from these downstream ions is zero.

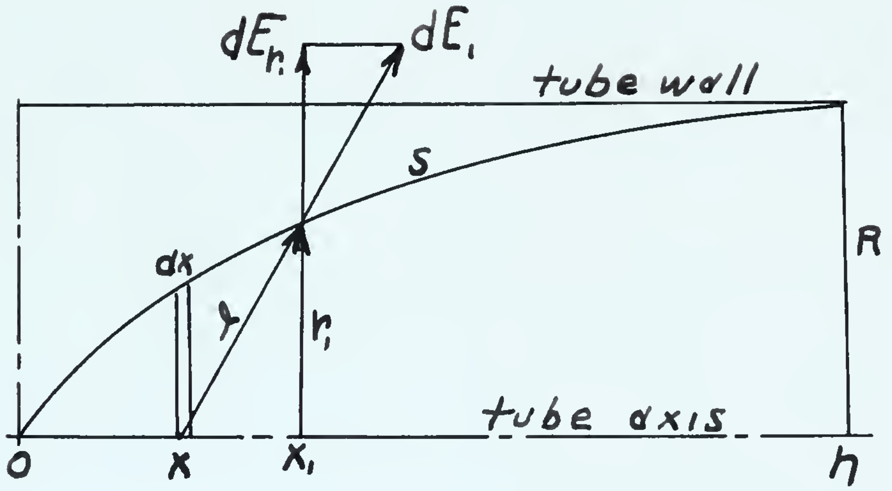


Figure 1

Path of Ions in a Moving Gas

Using notation previously defined, or as given by Figure 1, we have, Coulomb's Law,

$$dE_{r_1} = \frac{q\,dx}{l^2} \cdot \frac{r_1}{l}$$

$$E_{r_1} = \int_0^{x_1} \frac{r_1 q\,dx}{l^3} \quad ,$$

now

$$I = qu_x \quad ,$$

$$u_x = v - kE_x \quad .$$

We will now assume that the net effect of kE_x to be small compared with v so that $u_x = v = \text{const.}$ The above integral then becomes

$$E_{r_1} = \frac{r_1 I}{v} \int_0^{x_1} \frac{dx}{l^3} \quad ,$$

but

$$l = \left[(x_1 - x)^2 + r_1^2\right]^{\frac{1}{2}} = \left[x^2 - 2x_1 x + (x_1^2 + r_1^2)\right]^{\frac{1}{2}},$$

therefore,

$$E_{r_1} = \frac{r_1 I}{v} \int_0^{x_1} \frac{dx}{\left[x^2 - 2x_1 x + (x_1^2 + r_1^2)\right]^{3/2}}$$

$$= \left. \frac{(x - x_1)\, r_1 I}{v\left[(r_1^2 + x_1^2) - x_1^2\right]\left[x^2 - 2x_1 x + (r_1^2 + x_1^2)\right]^{\frac{1}{2}}} \right|_0^{x_1}$$

$$= \frac{x_1 r_1 I}{v r_1^2 \left[r_1^2 + x_1^2\right]^{\frac{1}{2}}} \quad .$$

Simplifying and dropping the subscripts,

$$E_r = \frac{xI}{v\ r\left[r^2 + x^2\right]^{\frac{1}{2}}} \quad .$$

Now, from elementary considerations,

$$r = \int_0^t v_r\ dt \qquad \text{and} \qquad v = \frac{dx}{dt} \quad .$$

Substituting for dt we have

$$r = \int_0^x \frac{kE_r}{v}\ dx \quad .$$

Inserting the previously developed expression for E_r,

$$r = \frac{kI}{v^2} \int_0^x \frac{x\ dx}{r\left[r^2 + x^2\right]^{\frac{1}{2}}} \quad .$$

Differentiating,

$$\frac{dr}{dx} = \frac{kI}{v^2} \frac{x}{r\left[r^2 + x^2\right]^{\frac{1}{2}}} \quad .$$

This equation is not readily integrable, but if r is small enough so that $\left[r^2 + x^2\right]^{\frac{1}{2}} \cong x$, we can integrate and obtain

$$r^2 = \frac{2kIx}{v^2} \quad ,$$

or

$$I = \frac{r^2 v^2}{2kx} \quad .$$

Except for a constant factor of 2, this expression is the same as that of Moreau-Hanot. The difference, though not explained, is not important in the subsequent discussion.

In the cases in which we will be interested, r will not always be small compared to x. Certainly R will be

of the same order as h, if not greater. If x is small compared to r, we can integrate to obtain

$$I = \frac{2\ r^3v^2}{3\ kx^2} \quad ,$$

which becomes, at the point where the ions strike the walls,

$$I = \frac{2}{3}\,\frac{R^3v^2}{kh^2} \quad .$$

Depending on the relative magnitudes of h and R, we would expect the variation of current to be somewhere in between the values predicted by these two equations.

EXPERIMENTAL INVESTIGATIONS

In view of the simplicity and potential usefulness of the gaseous ion charging system, and the small amount of work done on this method, it was decided to confine the experimental program to this method.

Objectives

Since the validity of the current and power estimates of the foregoing analysis depends entirely on the theoretical relationship given by Moreau-Hanot, it would appear desirable to check this formula experimentally.

Limitations on time and equipment prevented full scale tests of all variables involved. Objectives were limited to the following:

(1) Determination of variation of ion current with gas density, with transport distance, and with gas velocity.

(2) Determination of the effect of ionizing conditions and turbulence on current transported.

Apparatus

Design of the apparatus, as well as scope of the investigation, was tailored to fit availability of major

components. The principal requirement was for a reasonably large volume flow of gas at pressures controllable from one to several atmospheres.

This requirement led to the selection of a closed circuit system. In such a system, only the frictional pressure loss need be overcome by the power input.

The essential elements of the system are shown in Figure 2. A blower (a) forces gas through an ionizer (b) down an insulating tube (c). The gas then enters a long conducting tube (d) and finally returns to the blower inlet through an insulating hose and a valve, (e) and (f).

The ionizer consists of a needle placed at the center of a conducting cylinder. The needle is connected to a transformer-rectifier-doubler circuit which is capable of supplying a voltage variable from 0 to 30,000 volts.

The ion current reaching the collector was measured by passing it to ground through a vacuum tube voltmeter having an input resistance of 14 megohms.

The total ionizing current passing from needle to cylinder was measured by means of a similarly arranged vacuum tube voltmeter having an input resistance of 11 megohms.

Gas velocity was measured by a pitot-static arrangement connected to a manometer.

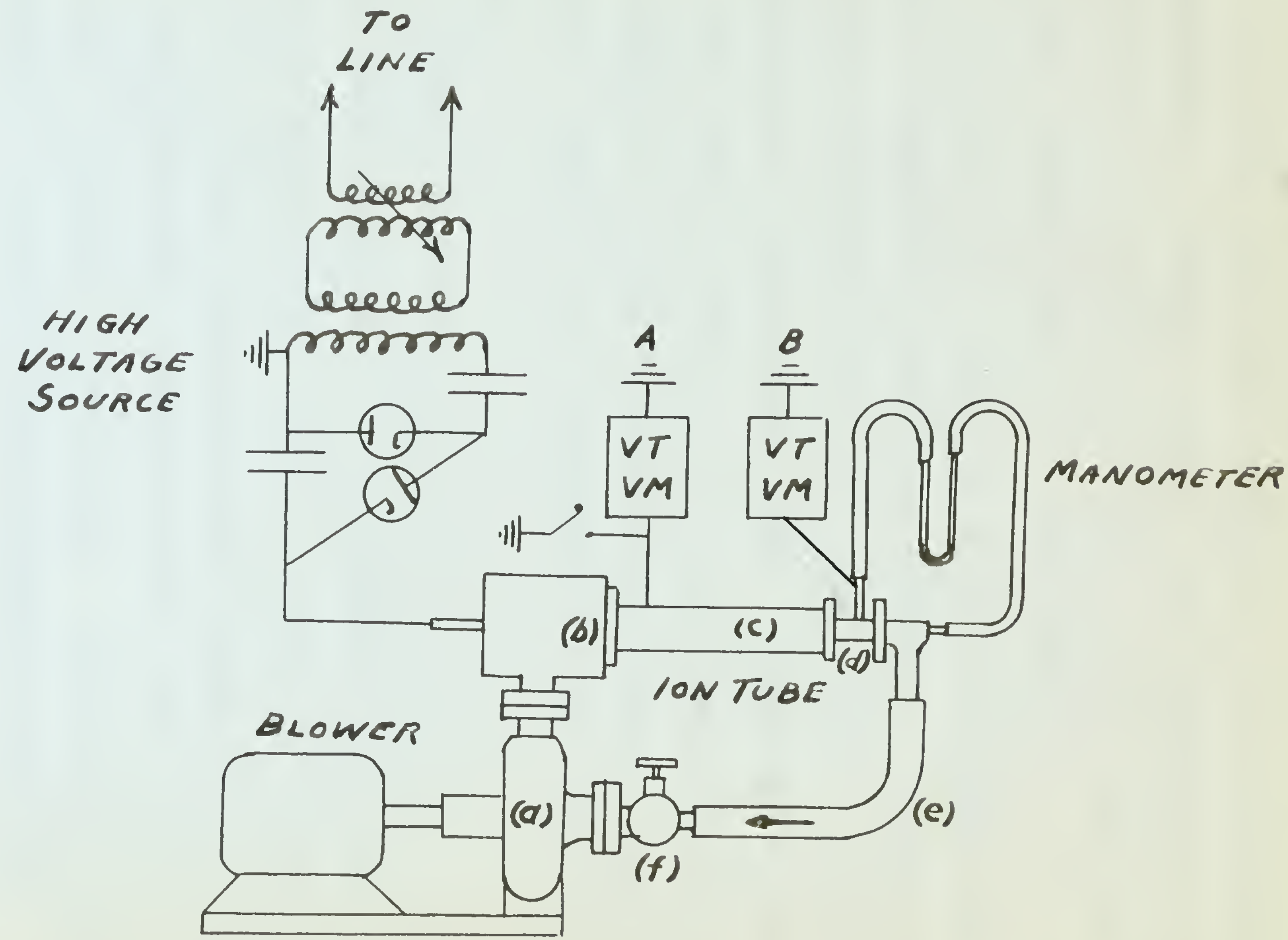


FIG. 2. SCHEMATIC OF EXPERIMENTAL SET-UP

Absolute gas pressure was measured by a simple Bourdon tube pressure gage.

Gas temperature was determined by an iron-constantan thermocouple in the gas stream. The indicator used was a Brown "Electronik" self-balancing potentiometer having a full scale sensitivity of 1.1 millivolts.

The blower was a Model 40 Durco centrifugal pump, having an impeller 10 inches in diameter. Bearings and seals were modified to make the pump operate satisfactorily on gas at twice rated speed. Power was furnished by a three phase, 3600 rpm., two horsepower electric motor.

Details of the ion transport tube may be seen from Figure 3. Figure 4 is a photograph of the entire apparatus.

Equipment for evaluating the diffusion due to turbulence alone consisted of a transparent tube which was mounted on the settling chamber in place of the ion transport tube. Flasks containing hydrochloric acid and ammonium hydroxide were connected to the air inlet and to the center electrode respectively. These flasks were connected to a nitrogen bottle through a regulator.

Procedure

The effect of gas density upon current transported

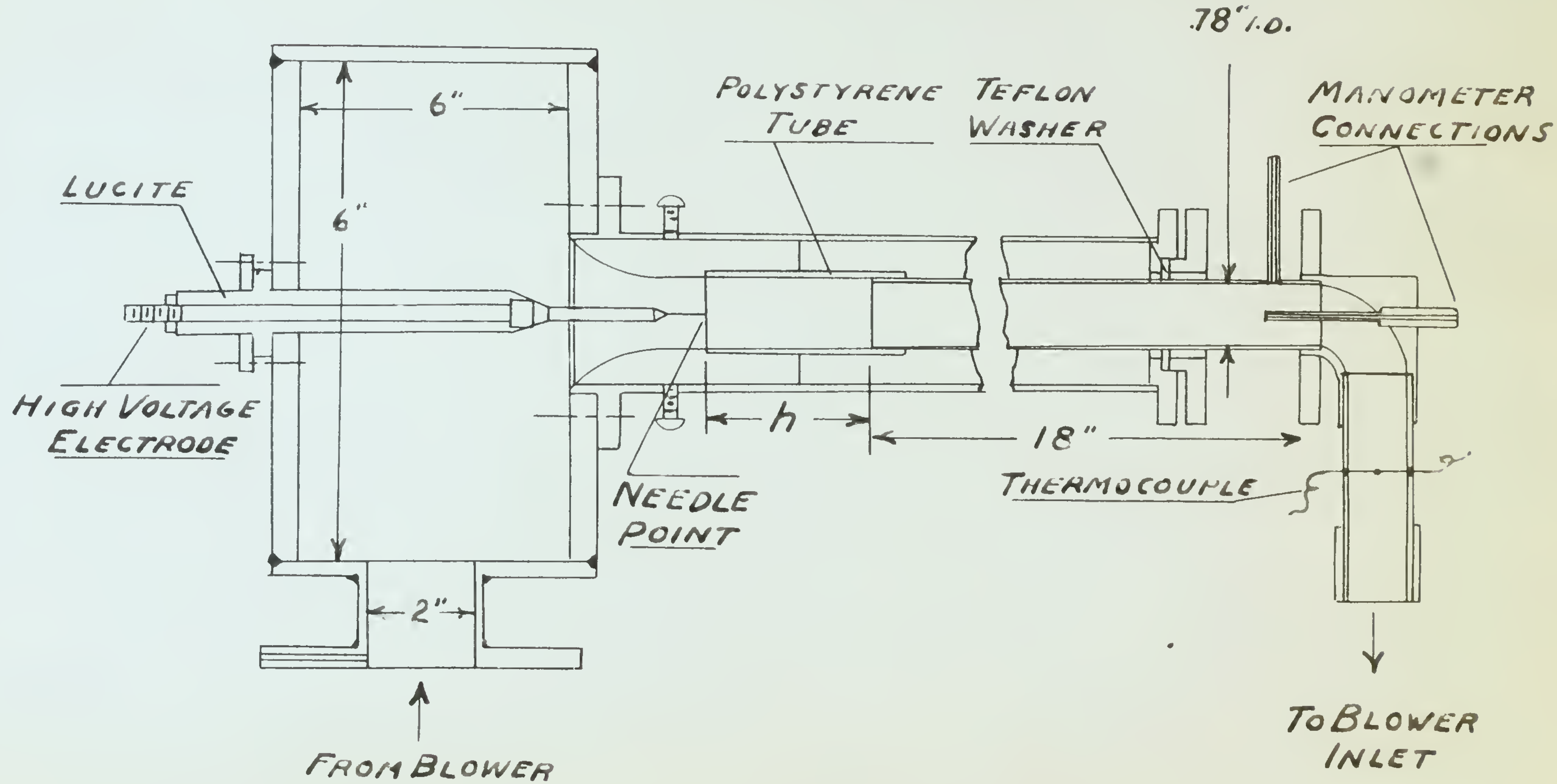
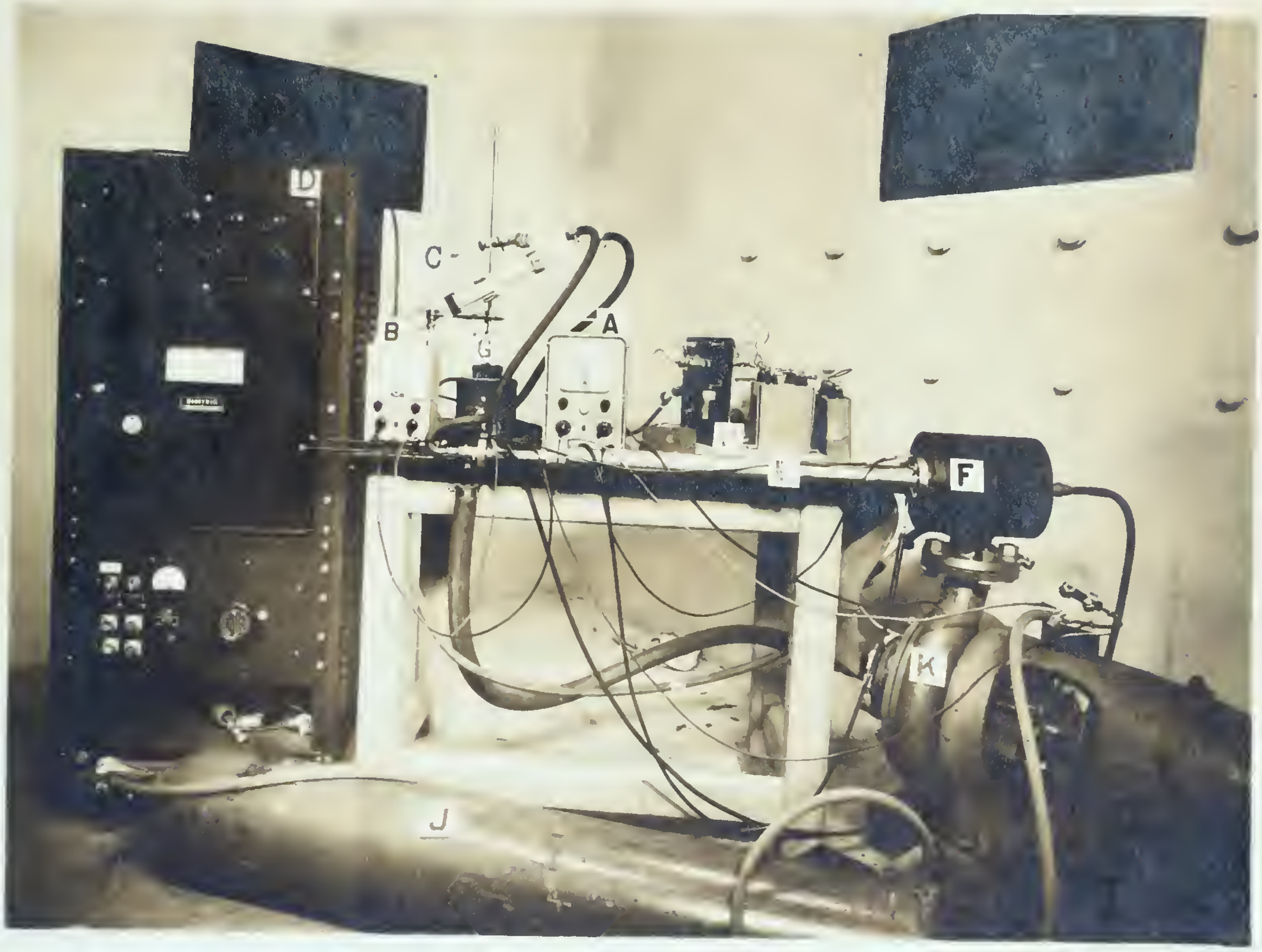


FIG. 3. DETAILS OF ION TRANSPORT TUBE



Key

A. Voltmeter A

B. Voltmeter B

C. Pressure gage

D. Millivoltmeter

E. Ion tube

F. Settling chamber

G. Variable transformer

H. High voltage source

I. Manometer

J. CO_2 tank

K. Blower

Fig. 4. Experimental Apparatus

was determined by first regulating the pressure to the desired value, then raising the ionizer voltage until a total current (I_1) from the needle to the cylinder was indicated on voltmeter A. (Fig. 2). This current was held constant in a given series of runs. The blower was then started, and, when full speed was reached, voltmeter B was read. This gave the total charging current, I.

Gas velocity was determined in advance by calibration of the blower.

The effect of velocity on charging current was determined using air from the building air supply. The blower was not used, but instead the ion transport assembly was connected to the compressed air line. Velocity and pressure were controlled by manipulating inlet and outlet valves. Several runs were made at different transport distances.

Variation of current with transport distance was obtained from a cross-plot of the previous runs. At short distances the leakage current due to the difference in potential between needle and collector tube was appreciable. This current was measured under conditions of no gas flow and subtracted from the total current measured with flow.

Temperatures were not recorded, since it was determined by several measurements that no appreciable devia-

tion from the constant room temperature of 70° F. occurred during any run. When pressure was increased, the temperature increased, due to the adiabatic compression of the gas already in the system. As the motor was started, the temperature would drop for an instant as the new cool gas passed the thermocouple, but heat transfer from the apparatus quickly brought the temperature back to ambient as the gas velocity increased.

The turbulence test was run on the shop air supply. Nitrogen pressure was set at about 10 psia. The nitrogen carried the hydrogen chloride into the airstream via a hole drilled in the settling chamber inlet flange. Similarly the ammonia was carried into the stream via the center electrode. The HCl and NH_3 reacted on contact to form NH_4Cl solid in very small particles, which then diffused to the tube walls under the influence of the turbulence. The chloride deposited on the tube walls where it struck. The distance from the tip of the electrode to the point where the deposit first formed could then be measured.

Results

To determine the variation of charging current with gas velocity, measurements of these two quantities were

taken over a range of velocities from about 25 to 200 ft./sec., holding the transport distance, ionizing voltage and gas pressure constant. These runs were repeated at transport distances of .5, 1, 2, 3, and 4 inches. The results are shown in Table 3 and Figure 5. Gas in all these runs was shop air at two atmospheres pressure. Ionizing potential was 10,000 volts.

The variation of charging current with pressure was determined at only one transport distance, namely, two inches. Pressure was varied from one to 7.7 atmospheres. Two series of measurements were taken, one at a total ionizing current of 18 microamperes and the other at 12 microamperes. The gas used in these tests was carbon dioxide of ordinary commercial purity. The data are listed in Table 4 and plotted on Figure 6.

The test to determine the turbulent diffusion was run using air at a pressure of one atmosphere. The ammonium chloride began to be deposited at a distance of 2 1/2 inches from the tip of the center electrode. No abrupt effect on the current was noted at this distance.

Table 3

Variation of Charging Current with Transport Distance and Gas Velocity

h(in.)	v(ft./sec.)	I(μa)	h(in.)	v(ft./sec.)	I(μa)
.5	55	1.0	3	43	.11
.5	59	2.1	3	50	.16
.5	61	1.6	3	69	.22
.5	70	1.7	3	90	.31
.5	90	2.8	3	112	.44
.5	130	4.0	3	150	.67
.5	150	5.8	3	190	.89
.5	205	6.1	4	35	.5
1	27	.6	4	56	.10
1	53	1.2	4	77	.16
1	86	11.8	4	103	.23
1	112	2.6	4	138	.37
1	142	3.0	4	182	.59
1	184	3.8	4	210	.78
2	29	.24	1	55	1.0
2	42	.25			
2	55	.33			
2	77	.47			
2	107	.70			
2	145	1.0			
2	200	1.5			

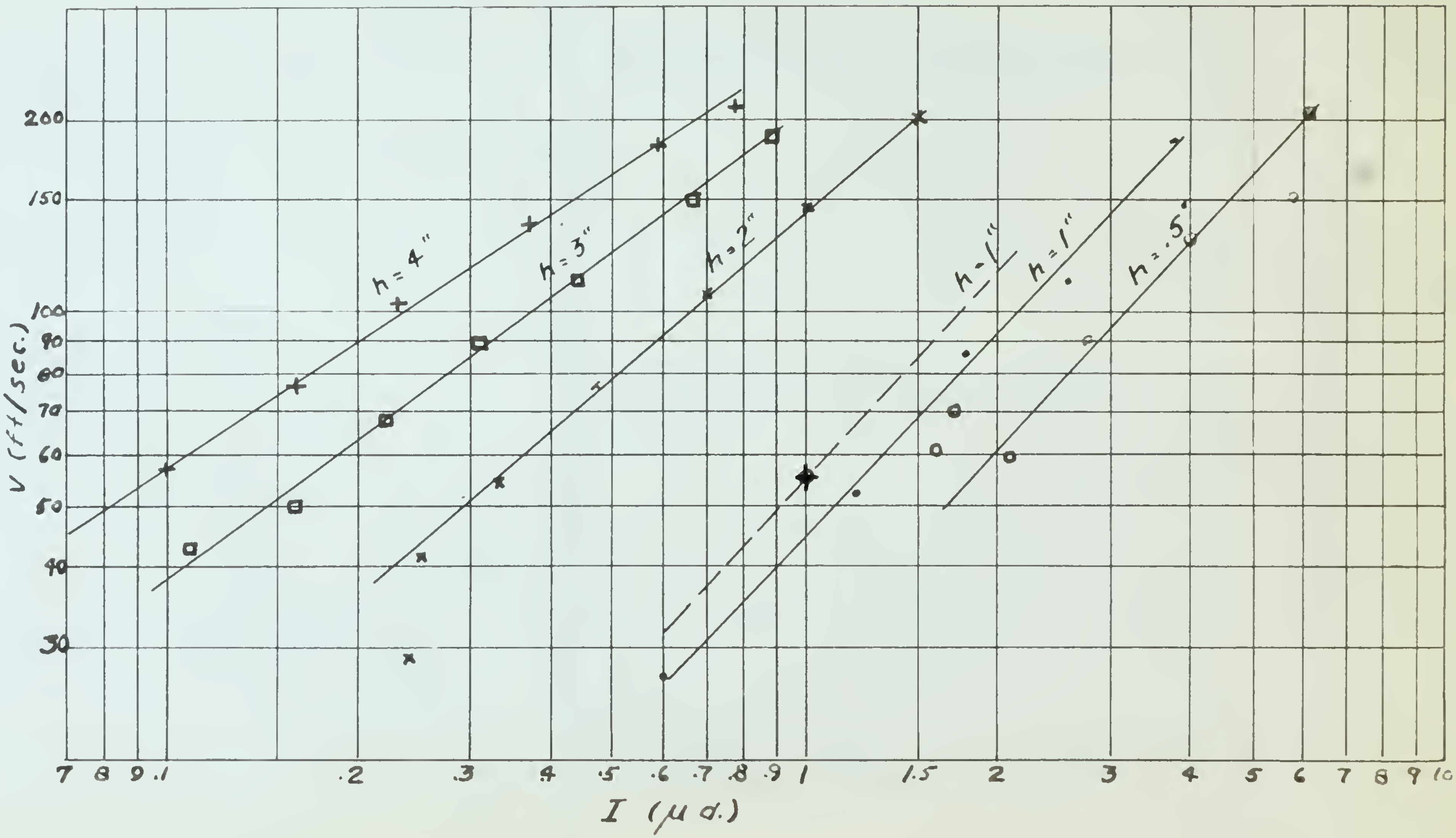


FIG. 5. VARIATION OF CHARGING CURRENT WITH VELOCITY

Table 4

Variation of Charging Current with Pressure
and Total Ionizing Current

I_i (μa)	P(atm.)	I (μa)
18	2	1.03
18	3	1.61
18	4	2.28
18	5	2.93
18	6	3.65
12	1	.4
12	2	1.14
12	3	1.43
12	4	1.86
12	4	2.00
12	5	2.86
12	5	2.14
12	6	2.86
12	6	2.86
12	7	3.50
12	7	3.14
12	7.7	3.70
12	7.7	3.71

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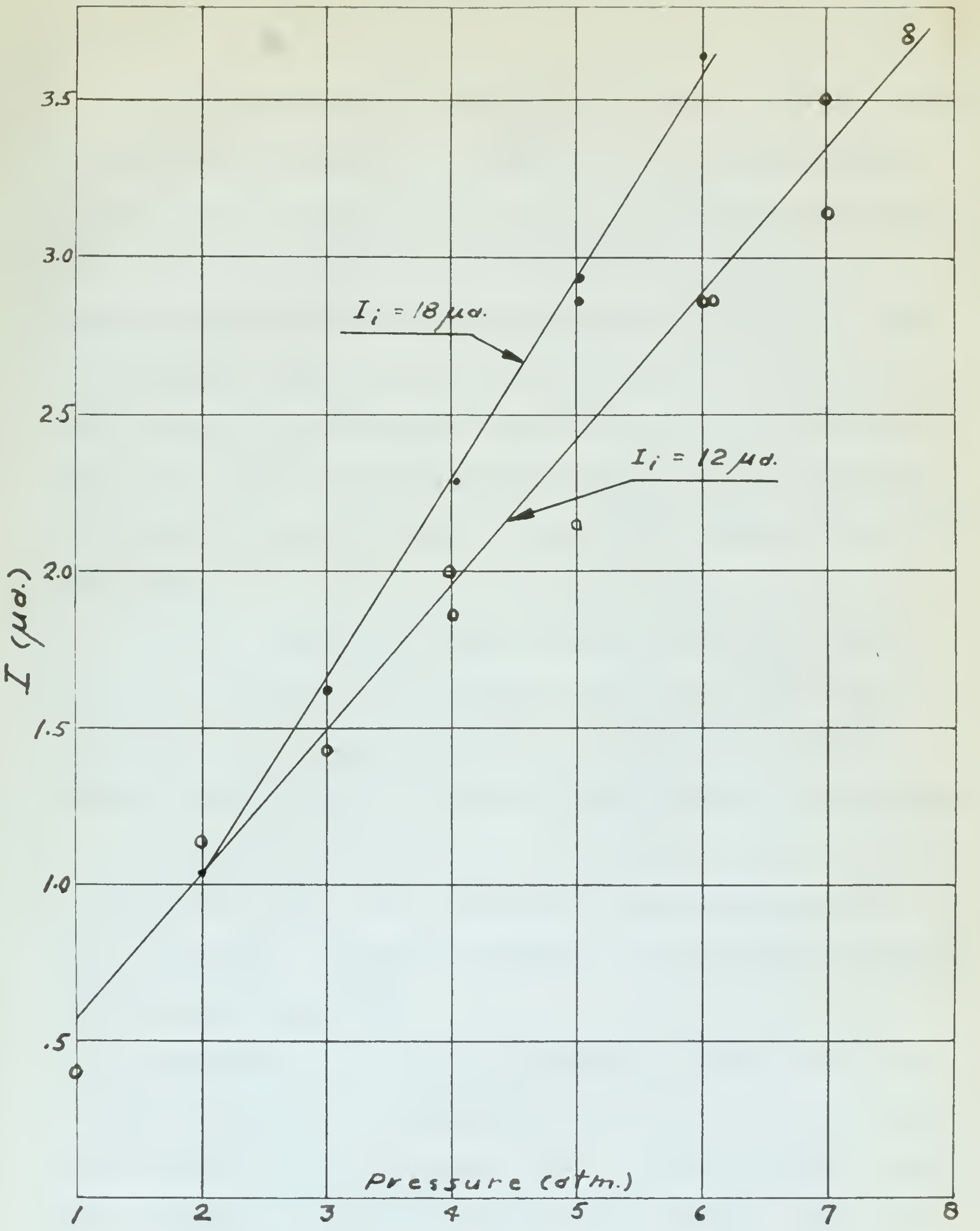

FIG. 6. EFFECT OF PRESSURE ON CHARGING CURRENT

DISCUSSION

The data obtained using air were taken with the space between the collecting tube and the outer support completely filled with paraffin. The resistivity of the paraffin varied between 20 and 100 megohms. Although the resistance was checked before, during, and after each run, and allowance made for it in calculating the values of ion current, it represents a possible source of error in the data. Were it not for the consistency of the points obtained, the results would be presented with much greater reluctance.

For the tests using CO_2, the apparatus was changed to the form shown. This change raised the resistances paralleling both voltmeters to substantially infinite values, which remained constant throughout all these tests.

The input resistance of each voltmeter was determined by using the other, the resistance scale of which had been previously calibrated against a 1 per cent precision resistor of 20 megohms.

The voltage scale of the charging current meter was calibrated against a flashlight cell which had previously been compared with a standard cell. Higher voltage ranges were checked by comparing overlapping values. The volt-

meter used to measure total current through the ionizer was not calibrated, but, since only relative values were important, this defect was not considered serious.

From the curves of Figure 6 it is easily shown that the charging current varies not with the square of the gas velocity, but more nearly as $v^{1.18}$. The most obvious cause of the discrepancy would be the turbulence of the stream. However, were this the correct explanation, we would expect the deviation from the v^2 of the formula to be greater at higher Reynold's numbers. Comparing with the results presented by Moreau-Hanot, which were obtained at values of R.N. four or five times that of the present work, we find the deviation there smaller instead of greater.

Moreau-Hanot does not report the conditions at the entrance to the tube, so it is not possible to compare the relative growth of boundary layers in the two pieces of apparatus.

It is possible to obtain some indication of the effect of tube size by comparing run 2 of Moreau-Hanot with data taken in the present experiments. Reducing the former data to the units used here, we have

$h = 2.95$ in.

$R = .985$ in.

$v = 111$ ft./sec.

$I \doteq 2.2\ \mu a.$

$P = 1$ atm.

From Figures 5 and 6 we obtain

$h = 3$ in.

$R = .39$ in.

$v = 111$ ft./sec.

$I = .44\ \mu a.$

$P = 2$ atm.

Computing the current we would expect with a radius of .985 inches on the basis of these data, considering the current to vary with the square of the radius as indicated for high values of $\frac{h}{R}$, we get

$$I_2 = I_1 \frac{P_2}{P_1} \left(\frac{R_2}{R_1}\right)^2$$

$$= .44 \times 1/2 \times \left(\frac{.985}{.39}\right)^2 = 1.4\ \mu a.$$

If we compute the current we would expect for low values of $\frac{h}{R}$, we get

$$I_2 = I_1 \frac{P_2}{P_1} \left(\frac{R_2}{R_1}\right)^3$$

$$= .44 \times 1/2 \times \frac{.985}{.39}^3 = 3.5\ \mu a.$$

We see that the experimental value of $2.2\ \mu a.$ lies between the two calculated values, as would be expected.

The effect of gas pressure on charging current shows

remarkably close agreement with theory. The variation in both cases is linear. The effect of changing the total ionizing current is essentially to introduce a multiplying factor.

The effect of ionizing conditions and geometry has been studied only briefly, but it will be noted that a variation in total ion current causes the charging current to change by a factor which is essentially a constant for a given total ion current (Figure 6). The analysis does not predict that the charging current will vary at all with total ionizer current, i.e., with ionizer voltage. The theory was developed on the basis that all ions were formed at the needle point and thereafter moved through the carrying gas only by the influence of their mutual repulsion. It is obvious that this is not precisely the true picture, for a strong field is necessary to create the ions. This field will cause some radial motion of the ions before they move far enough down the tube to be essentially free from this ionizing field.

A possible explanation of the effect of the higher total ion current may be the following: a higher total current between needle and cylinder means a higher space charge in the enclosed volume. This space charge lowers the field strength near the wire, and raises it near the

cylinder. The ions will thus move more slowly in the early part of their history when the current is high. This will permit them to be "freed" from the ionizing field while closer to the axis of the tube. Thus they can be carried further down the tube before striking the walls, or a greater charge could be carried the same distance.

The simplified theory also predicts that the current transported will remain constant with distance until a certain critical distance is reached, at which point the current will drop to zero. A cross plot of the data of Figure 5, taken at a velocity of 100 ft./sec., is shown in Figure 7. This graph shows the current to vary inversely with the distance in a rather continuous fashion. Apparently the ions are either formed at different distances from the needle point or they move at different velocities after leaving the point, or both. The latter presumption is reasonable, since in the region of the brush discharge the field varies discontinuously in a random fashion and the effect of turbulence also would be to encourage a random scattering of the ions.

These comments on the effect of total ion current are essentially speculative. More investigation and analysis is required before an adequate explanation can be offered. Some tests were also made on the effect of

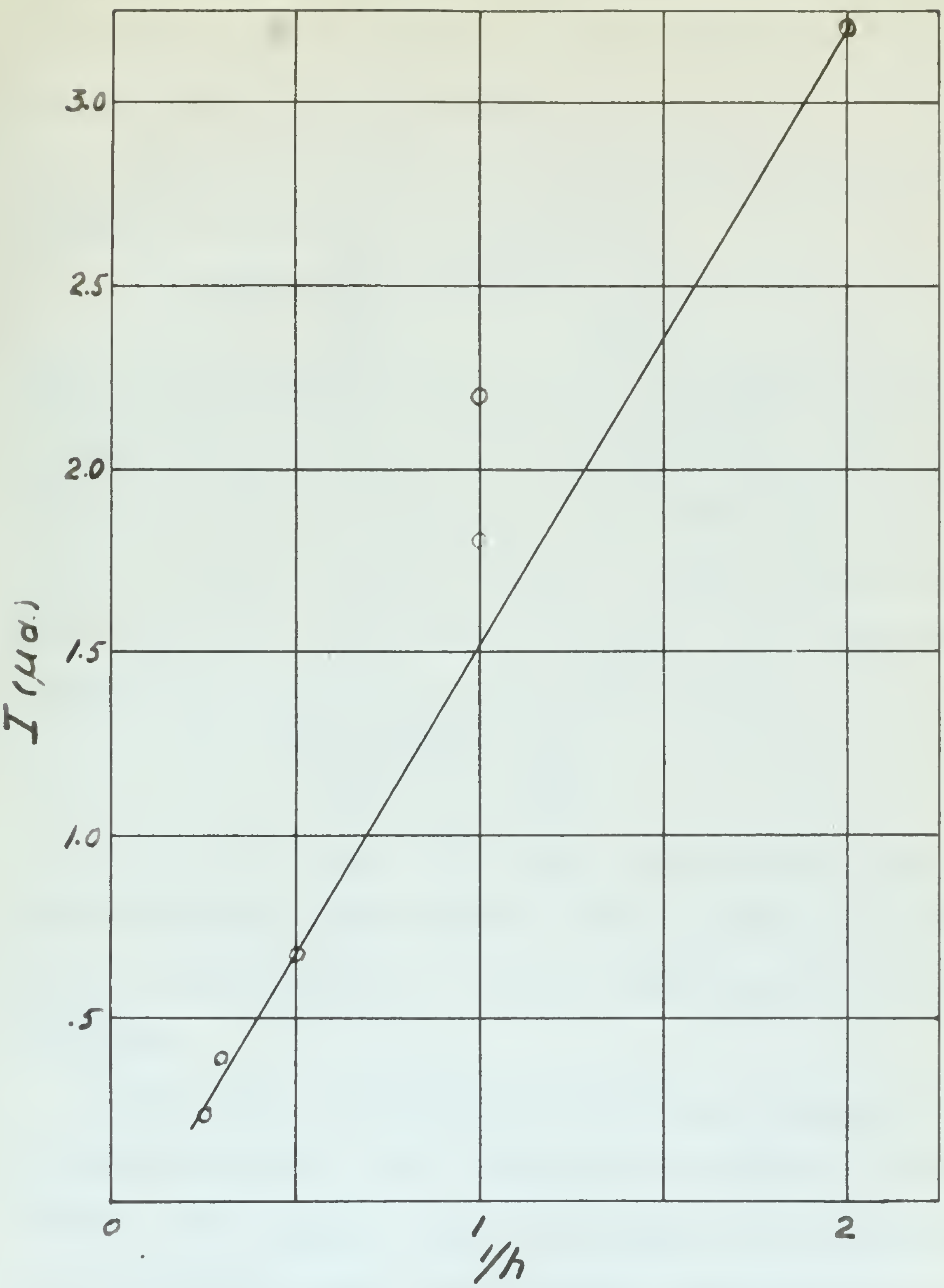

FIG. 7. VARIATION OF CHARGING CURRENT WITH TRANSPORT DISTANCE

ionizer geometry. Although definite effects were noted, the results were quanitatively inconclusive. More study in this area is needed also.

Correlating theory and experiment as best as we can at present we arrive at the formula

$$I = \frac{3.27 \times 10^{-4}\, u^{1.18}\, R^2}{k_o h} \frac{\rho}{\rho_o},$$

where I is in microamperes, u is in ft./sec., R and h are in feet and k_o is in (ft./sec.)/(volt/ft.). The constant has been adjusted to fit the experimental data most closely for h = 2 inches and I_i = 12 μ a. This relation holds most closely for large values of h/R. For cases where h/R is small, the relation will be more nearly

$$I = \frac{.06\, u^{1.18}\, R^3}{k_o h} \frac{\rho}{\rho_o}.$$

If we wish large currents, it is apparent from the above expressions that we must have a high gas density and low transport distance. A large tube size is even more important.

In general, an increase in tube size means an increase in power required. The volume rate of flow at constant velocity will increase with the square of the tube radius, and the friction drop will probably not decrease so rapidly. Further analysis may show some advantage in using a concentric arrangement for charging and return paths, with

the return path on the inside. Since the radial velocities of the ions are smaller at larger values of R, we would expect some gain in charging current even if the width of the charging annulus were no greater than the radius of a single tube of the same area.

It is possible that power requirements for the gaseous ion charging system will prove excessive. Undoubtedly it will be necessary to hold the pressure drop through the circuit to an absolute minimum in any specific design.

CONCLUSIONS

On the basis of the investigations made, we may draw the following conclusions:

(1) If the experimental ionizing conditions are duplicated, the relationship between current, tube radius, ion mobility, gas density, velocity and transport distance for a gaseous ion charging system may be represented, for high values of h/R, by the following equation:

$$I = 3.27 \times 10^{-4} \frac{v^{1.18} R^2}{k_o h} \frac{\rho}{\rho_o} ,$$

where v is in ft./sec., R and h are in feet, k_o is in (ft./sec.)/(volt/ft.), and I is in microamperes. For low values of h/R the equation becomes

$$I = \frac{.06\ v^{1.18} R^3}{k_o h} \frac{\rho}{\rho_o}$$

(2) The radius of the ion tube should be made as large as geometric and structural considerations permit.

(3) Power consumption is likely to be high. Care should be taken in any specific design to minimize pressure losses in the charging circuit.

(4) The gaseous ion system might prove useful where high currents and long life at low maintenance are desired. The transport medium should require no servicing whatsoever, whereas belts wear out rather rapidly.

(5) Further tests are required to determine the influence of ionizer geometry and operating conditions.

(6) Further tests would be desirable to determine the effect of gas density up to perhaps 500 pounds per square inch using sulfur hexafluoride gas.

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